



Lunar Power Hibernation for Surviving the Lunar Night

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Lunar Power Hibernation for Surviving the Lunar Night



Power Hibernation is an approach to dramatically extend capabilities and duration of Low-Cost Robotic Lunar missions by exploiting the common 18650 Li-Ion Battery Cell's ability to tolerate and recover from extreme cold of the lunar night.

- Surveyor Experience
- Lunar Thermal Environment and Mission Constraints.
- Li-Ion Low Temperature Survival
- Power Hibernation Assumptions
- Hibernation Power Architecture and Dawn Operations
- Cryo-Temperature Electronics Technology
- Power Hibernation Architecture Development

Surveyor Experience: Surviving the Lunar Night

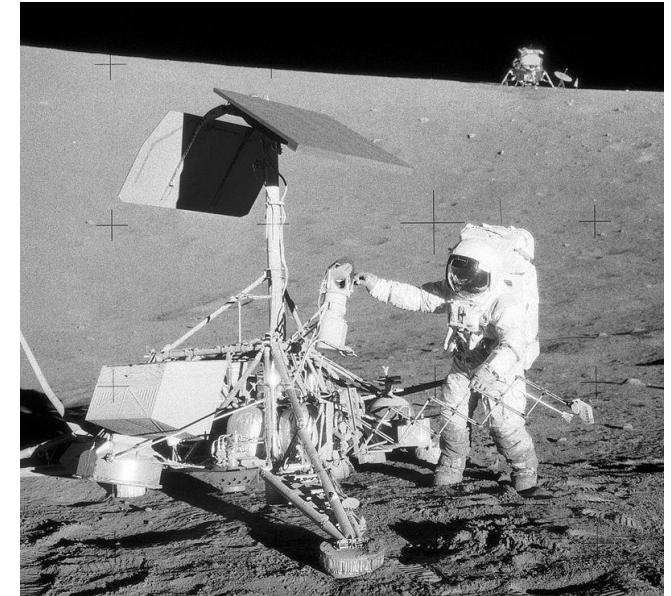


Common Misconception: “Spacecraft batteries cannot take extreme lunar night temperatures and will die”. ***This is Not True***

- *Recent studies show that common lithium-ion cells can survive*
- *Success depends on safely restoring the power system at lunar dawn*

Surveyor Missions Experience (1966-1968)

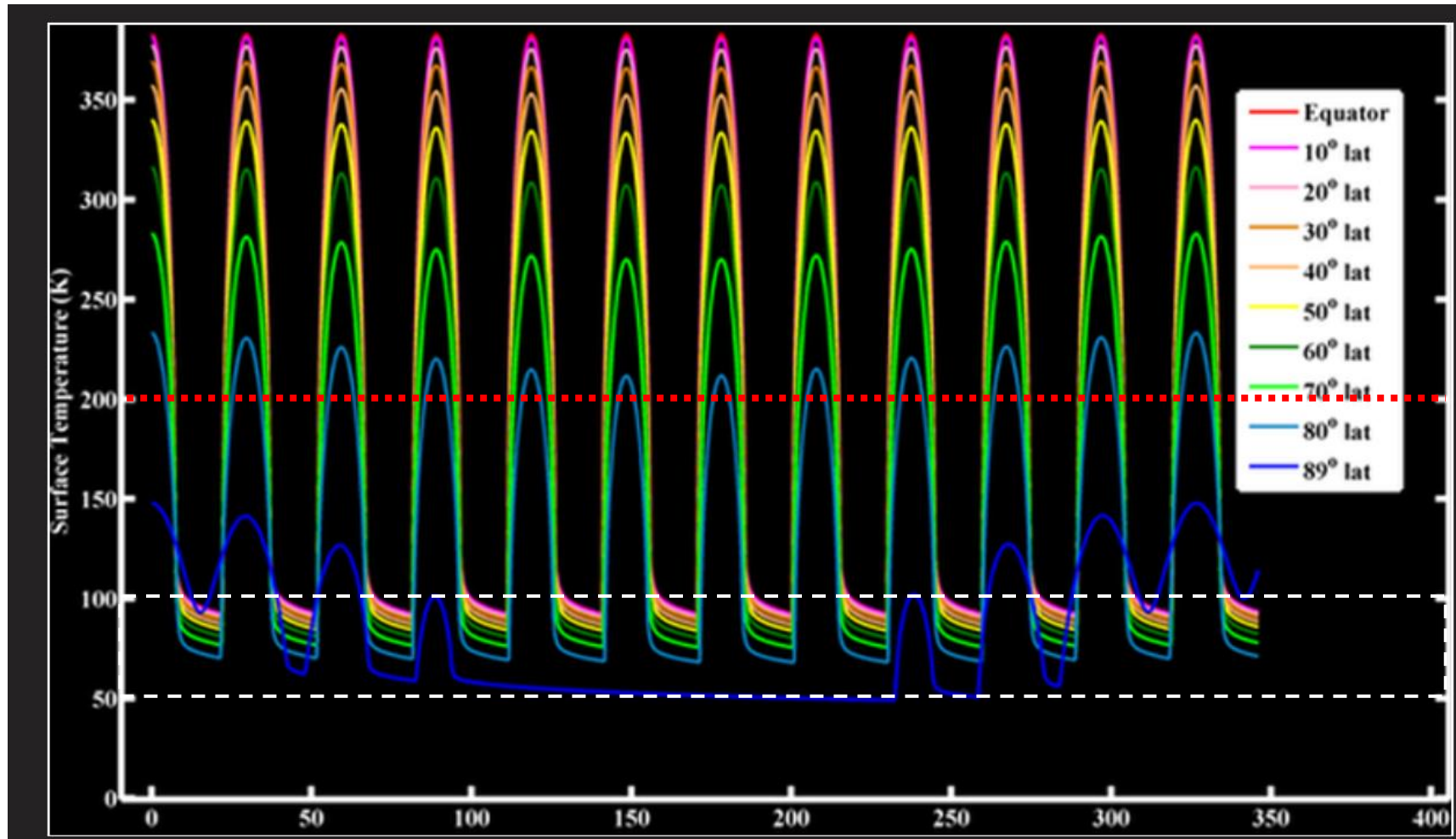
- Surveyor was not designed for Night Survival
- RTG technology still under development
- Multiple Surveyors did indeed survive the night
 - Used Silver-Zinc Batteries
 - Most Surveyor missions partially survived beyond one lunar cycle.



NASA Photo

LRO DIVINER: Lunar Day/Night Temperature Range by Latitude

Thermal model calculations of monthly and annual lunar surface temperature variations at various latitudes.



< - Li-Ion Battery
Approx. Freeze
Temperature

< ---- Lunar Night
Temperatures are
extremely cold
everywhere

Permissions per Dr. N Petro/NASA GSFC and Dr. D Paige/UCLA

Environment and Mission Constraints



Extreme Thermal and Illumination Environment

- Day temperatures span from 100K to near 400K based on latitude
- Night temperatures span 50-100K for all latitudes
- Non-Polar latitudes night durations ~354 hours
- Polar Regions have very low sun angle, varying sun/shade cadence and durations
 - Illumination affected by site elevation and topographical features casting shadows
 - Seasonal Variations (sun drops below horizon in lunar winter for 4 ½ Months)
 - Polar Day Time high temps still below battery operating temperatures

Low-Cost Mission Constraints - Commercial Lunar Payload Services (CLPS)

- CLPS landers are low cost, short development cycle
- CLPS landers are not likely to operate much beyond a single lunar daylight period
- Hibernation is the most viable option for robotic survival

Li-Ion Low Temperature Survival



Indian Space Research Organization (ISRO) published work on Hibernation

- 2018 ISRO investigated 18650 Li-Ion cell passive lunar night survivability.
 - Evaluated 3 manufacturers of 18650 Li-ion cells.
 - Subjected them to 14 day lunar night at -160°C (in vacuum)
 - Cells recovered charge capacity with no apparent damage or degradation
- ISRO published a power architecture concept for Hibernation
- Its not clear if hibernation capability was on-board Chandrayaan-2 lander
 - Lander crashed in 2019
 - *(It is clear that they were thinking about it.)*
- “Flash-Freezing” of Li-Ion batteries
 - Industry Seeking lower cost means of safely transporting Li Ion Cells.

18650 Li Ion Cell Investigation at NASA Glenn

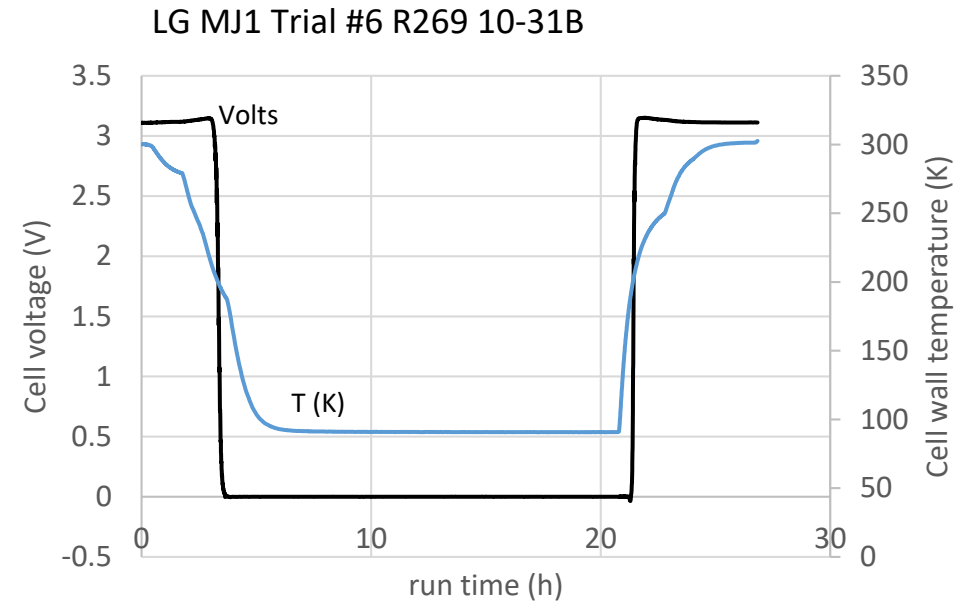


Preliminary Tests Performed at 1 Atmosphere

- LN_2 Vapor chilled to 80K (-193°C)
- (3 of 5 Survived)
- Safety Device Trips in 2 of 5 Cells

Root cause of trips is not fully understood

- Strongly suspect seal leak and trapped LN_2
- Chilled Cells have negative pressure
- Only 20 mg of trapped LN_2 would rupture the pressure relief disc.



Figures Courtesy of W. Bennett NASA Glenn

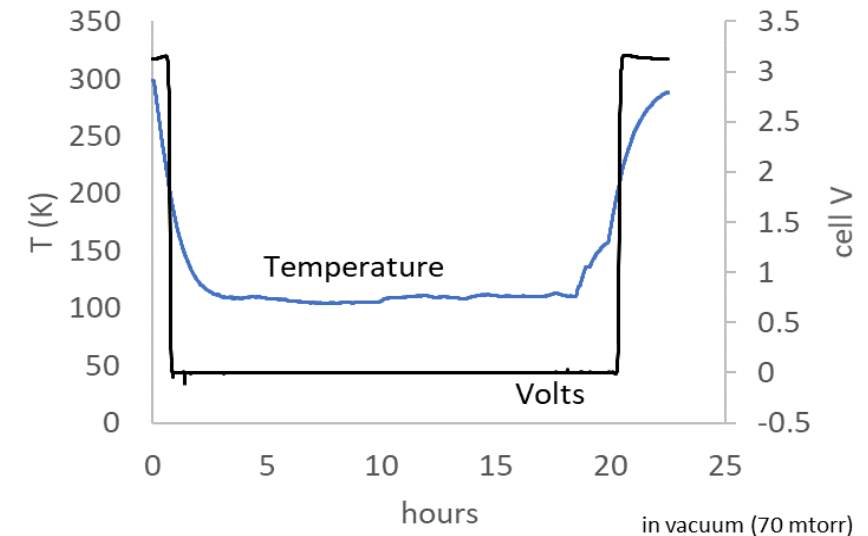
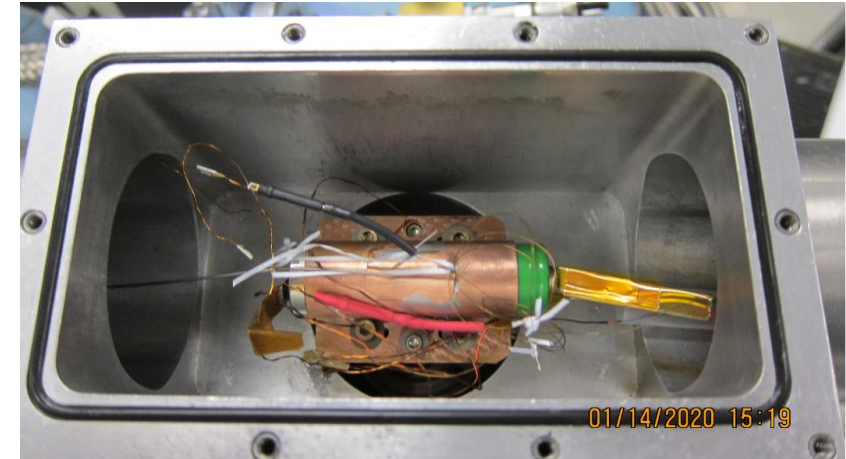
Cell Hibernation Investigation at NASA Glenn

Tested with Cryocooler in Vacuum



Revised Test Setup for full vacuum

- Improved representation of lunar environment
 - Vacuum chamber pressure at ~70 mtorr
 - Cryocooler chilled and held near 100K.
 - Eliminated pressure reversal
 - Eliminated risk of LN₂ Intrusion
- Voltage dropped to zero below 200K
- Voltage recovers when warmed above 200K
- 4 of 4 cell trials in vacuum were successful
 - *No CID Trips or Disc Ruptures*



Photos courtesy of W. Bennett NASA Glenn

Power Hibernation Assumptions



Lowest Temperatures occur just before Lunar Dawn

- Non-polar latitudes we assume night is ~354 hours.
- Polar Regions subject to multiple short (Dusk-Dawn) cycles
- Active Cold Capable Controls needed to manage array voltage.

Assume that Li-Ion Batteries will survive the Lunar Night

- Batteries Passively Survive the cold without loss of capability
- Batteries must be isolated from main bus prior to Dawn
- Requires “Cold Capable” Controls to manage the Battery Recovery
 - Pre-Heating and Pre-Charging are required while isolated
 - Battery reconnected when temperatures and voltages return to normal

Note: “Cold Capable” electronics are capable of operating at lunar night temperatures.

Power Hibernation Assumptions



Solar Arrays expected to Survive and Generate Power at Lunar Dawn.

- Photovoltaic Arrays are tolerant of cryogenic temperatures.
- PV Arrays at cold temps will cause high open-circuit voltages.
- Requires Cold Capable power controls to manage array power

Assume Avionics Passively Survives

- Avionics will need to be qualified to passively survive lunar night temperatures
 - Not required to operate below normal temps
 - Avionics thermally conditioned (preheated) prior to activation
- External Cold Capable *Power Controls* to manage temperature recovery

Power Hibernation Architecture



Main Bus Control (MBC) is Active at Cryo-temps:

- Main (Power) Bus Control incorporates “Dawn Mode” functions
- Dawn Mode
 - Must be “cold capable” of activating and operating at low temps
 - Operates on Solar Array power alone
 - MBC must operate when flight computers are Not Available
 - Manages PV Arrays and Main Bus Voltage
 - Manages Battery State (through Battery Management System)
 - Enables/Disables System Loads via Power Inhibits. (Avionics and Payloads)

Hibernation and Dawn Operations



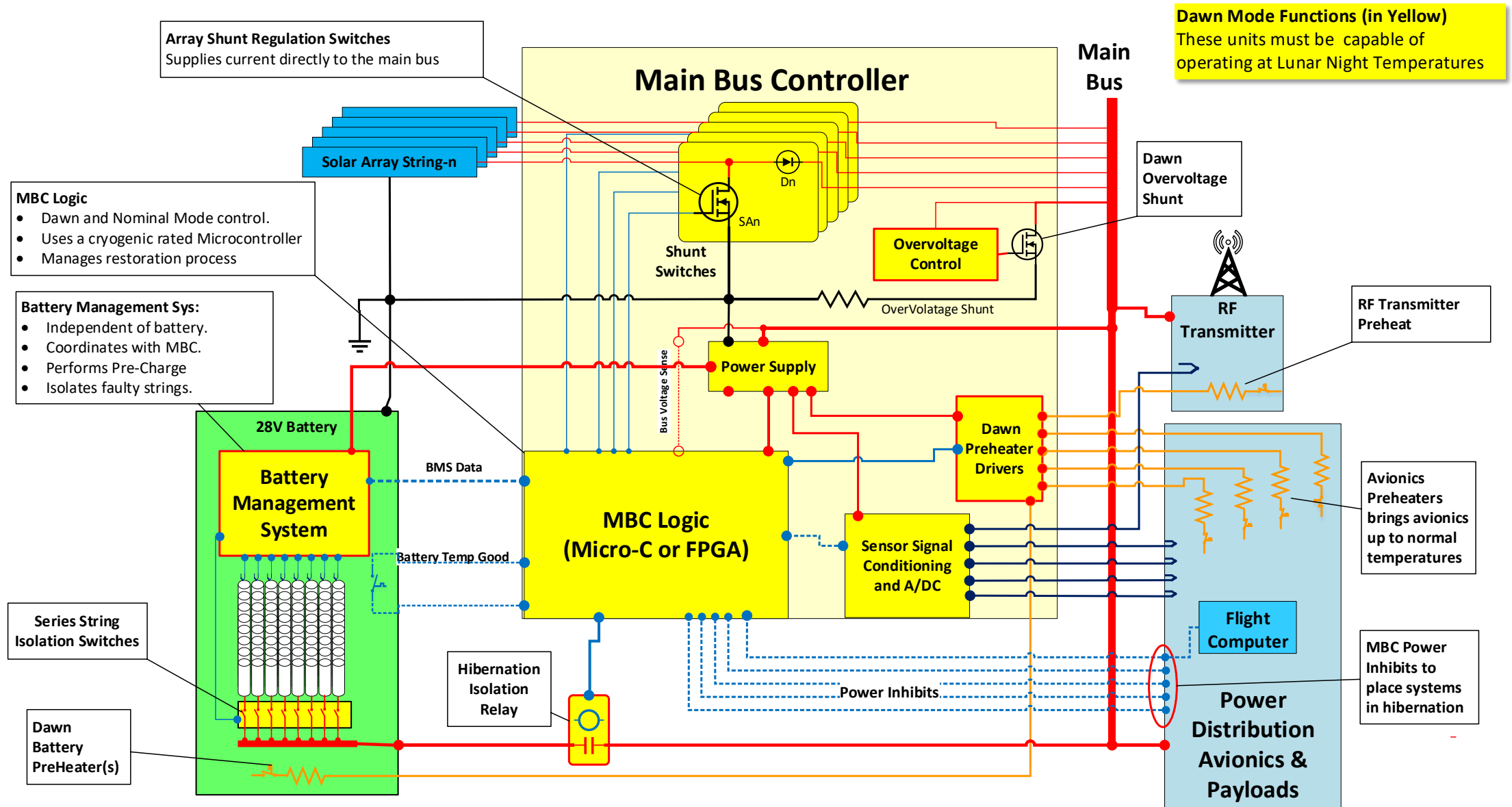
Lunar Dusk:

Point Arrays toward Dawn, Shut-Down Loads, Isolate Battery, Wait for Dawn

Lunar Dawn: (first illumination, coldest temperature)

- Array Open Circuit Voltage limited by a Over-Voltage Control
- MBC in Dawn Mode operates on Solar Array power alone (*Battery still Isolated*)
- MBC manages thermal conditioning (Pre-Heaters) for battery and avionics
- Battery Management System (powered by MBC, also operates in extreme cold)
 - Monitor battery temperatures and voltages during Dawn Pre-heat
 - At normal temperature BMS pre-charges battery to match main bus voltage
 - If a string fault is detected the BMS isolates the faulted string
- MBC Closes Isolation Relay: Reconnects Battery to Main Bus- **Dawn Mode Complete!**
 - MBC clears “Power Inhibits” allowing system to boot-up as normal

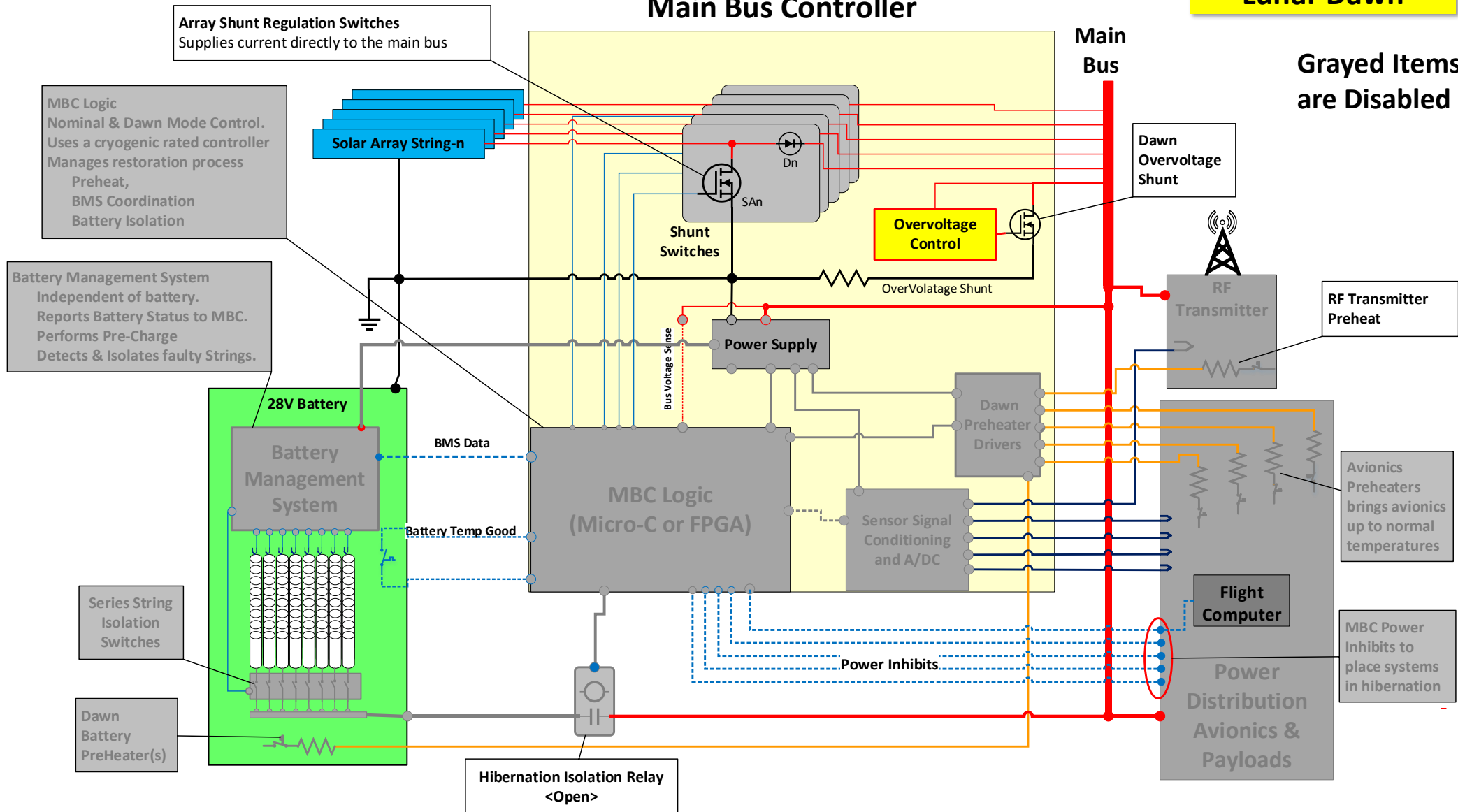
Power Hibernation Architecture



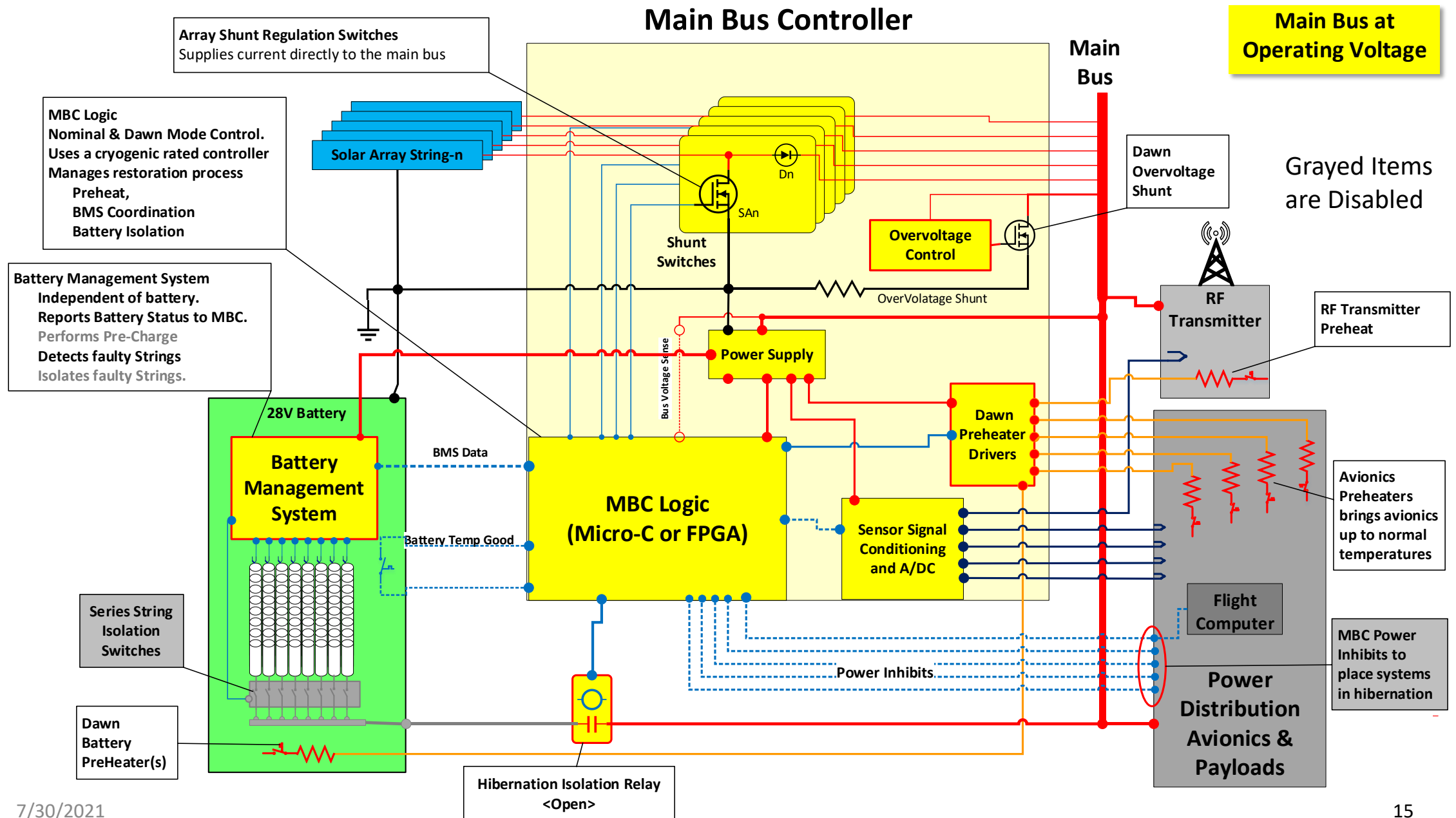
Dawn Mode Functions

Lunar Dawn

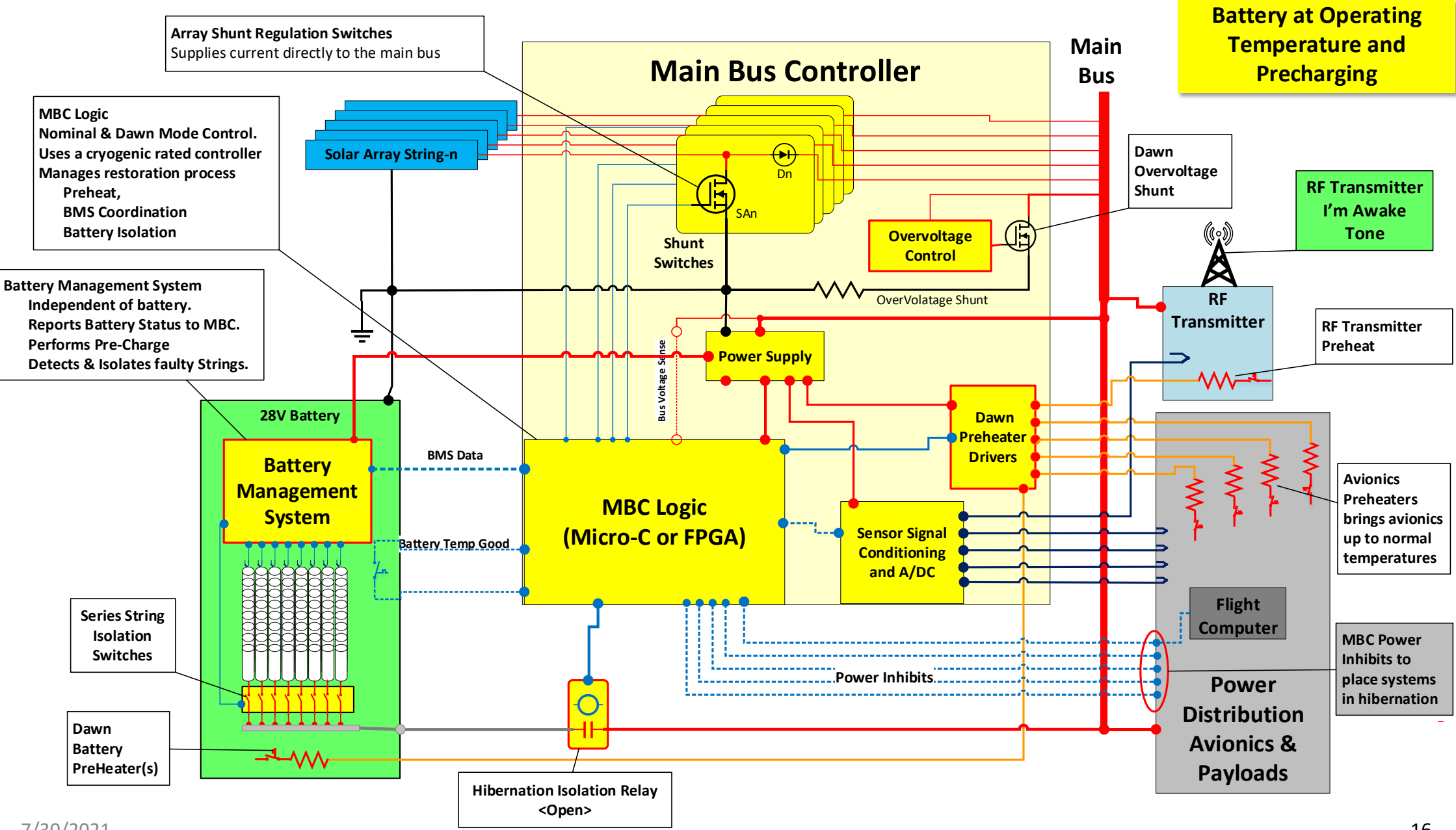
Grayed Items are Disabled



Dawn Mode Functions

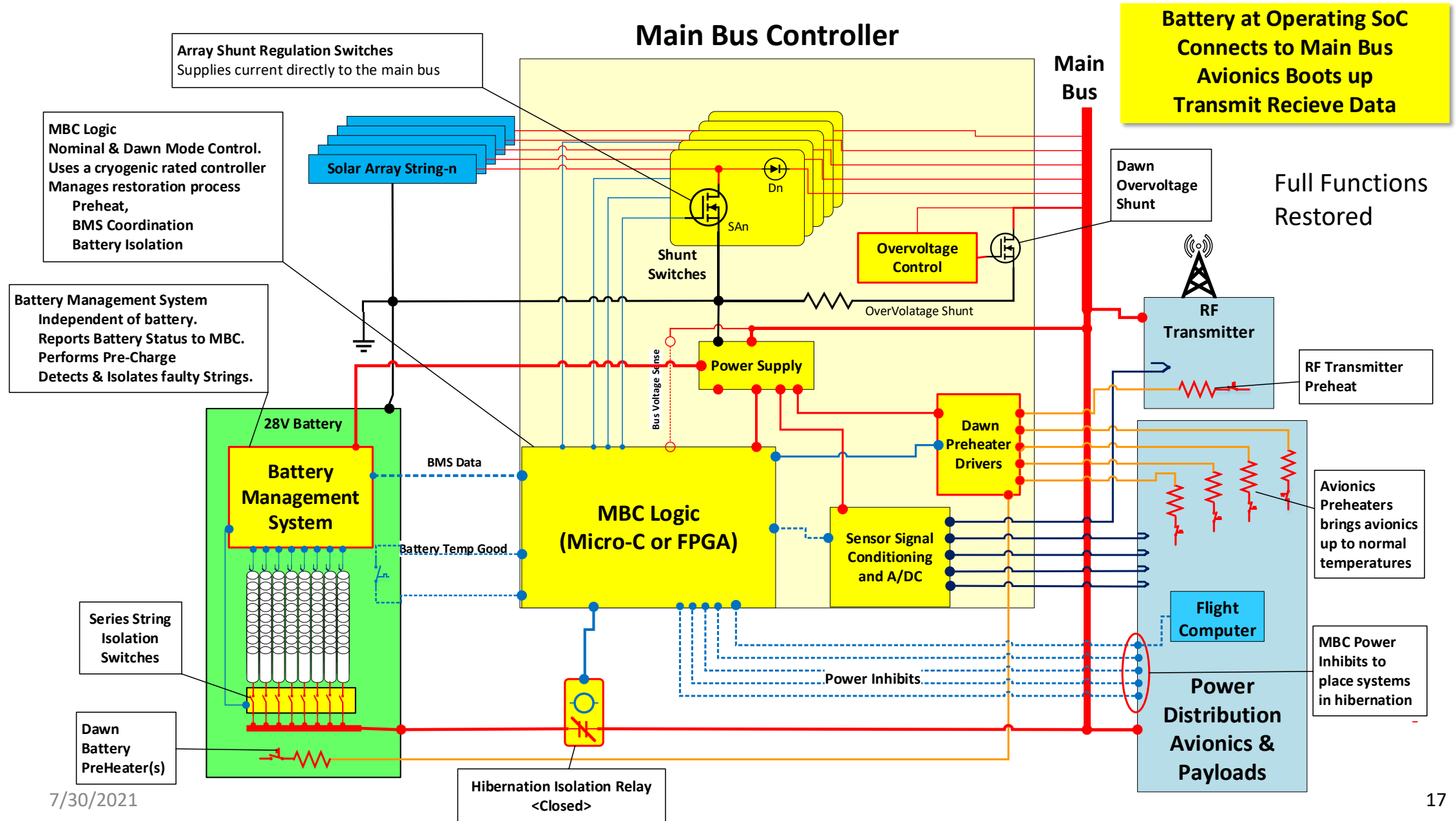


Dawn Mode Functions



Dawn Mode Complete

Main Bus Controller



Hibernation Battery Development



Li-Ion Cell work

- NASA preliminary testing was limited to mostly one source
- ISRO tested 3 manufacturers (were not identified)

Future Hibernation Tests

- Evaluate a wider range of cell manufacturers
- Testing of cells from lots certified for human space flight
 - Strategic procurements of 40,000-60,000 cell lots
 - Controlled supply “Chain of Custody”
 - Establish Statistical Confidence
- Evaluate alternate cell formats (20700, 21700)
- Establish safe cell hibernation cycle and State of Charge guidelines
- Investigate pre-thaw Fault Detection (*cells are safest when frozen*)

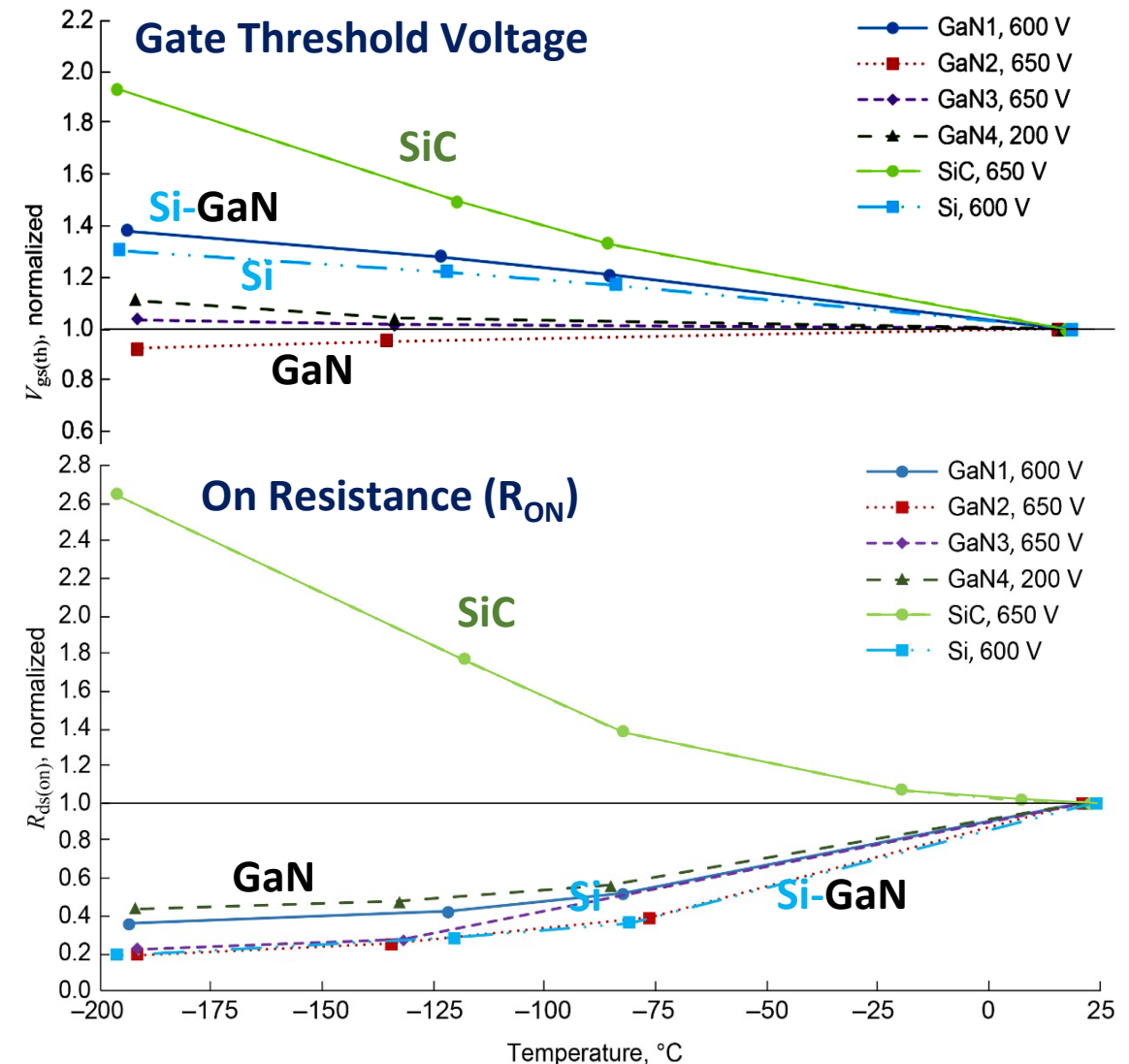
Cryo-Capable Electronics Technology



Gallium-Nitride (GaN): (LN₂ testing)

- GaN suited for low temp operations
- Tests indicate good low temp performance
 - GaN innately more efficient than Silicon
 - Gate Threshold Voltage: Stable to -196C
 - ON Resistance: Improves at low temps
- GaN used in Space Power and RF Comm
- GaN is more Radiation Tolerant than Si or SiC
- **Si-GaN Switch** (GaN with Silicon front end)
 - Overcomes Gate Over-Voltage sensitivity

Figures Courtesy of Marcelo Gonzalez NASA Glenn



Cryo-Capable Electronics Technology

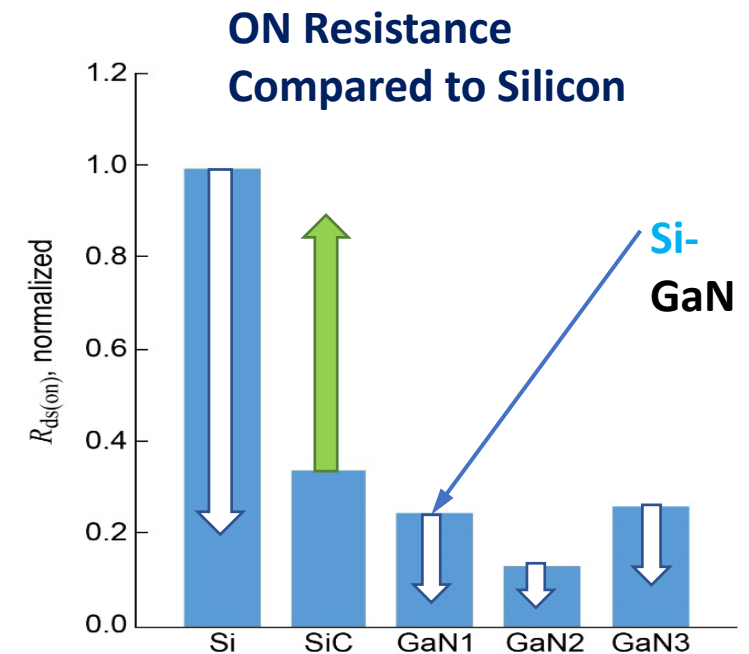


Silicon-Carbide: Poor low temp performance as an enhancement mode switch

- SiC is subject to “Carrier Freeze-Out”
 - Threshold Voltage climbs
 - On-Resistance $R_{ds(on)}$ climbs

Silicon Devices:

- Silicon still dominates Digital Applications
- Wide availability, low cost, huge Body of Knowledge
- Quantum Computing developments are finding Silicon FPGAs operating down to 4K.



Figures Courtesy of Marcelo Gonzalez
NASA Glenn

Power Hibernation Architecture Development



Hibernation Cell/Battery Development

- Fully characterize electrochemistry through the hibernation thermal cycle.
- Determine safe state of charge level.
- Thermal Management (uniformity temperature, uniform cell output)
- Battery Management System (cell monitoring, isolating faulty strings, pre-charge control)
- Battery Life Testing to demonstrate multiple lunar cycles

Cryo Temperature Electronic Device Studies

- Gallium-Nitride, in power regulators and analog applications
- Cryo-Temperature Digital and Analog device evaluations (Controllers and Instrumentation)

Main Bus Controller: Dawn Mode Electronics

- PV Array Management Approach (Sequential Switching or Shunt)
- Stabilizing main bus power while battery is disconnected
- Pre-heater Controls



Need Collaboration with the Space Avionics Community

Most Avionics need only Passively Tolerate the extreme cold.

- Avionics will need additional qualification testing to prove passive tolerance
- NASA has succeeded in modifying COTS circuits for cryogenic operations.
- Circuit Boards:
 - Conventional FRP circuit board material is remarkably cold tolerant.
 - Minimize Thermal Stress by minimizing temp gradients and dT/dt .
 - Fortunately, Lunar environment changes slowly (few degrees/hour)

Hibernation depends on Active Cold Capable Electronics

- Identify cold/radiation tolerant Digital Logic, (Microprocessors and FPGA)
- Analog circuits struggle with stability at low temperatures
- Exploit GaN low sensitivity to temperature to broader Analog Applications.
 - (Instrument Amplifiers, Control Amplifiers, Power Regulators.)

Lunar Power Hibernation for Surviving the Lunar Night Summary



Hibernation Enables Low Cost Missions Achieve Multi-Lunar Cycles

- 18650 Li-Ion cells demonstrated a night survival capability
- “Passive Hibernation” minimizes changes to existing hardware
- Reduced dependency on costly radioisotope heat and power sources
- Applicable to lunar robotics and lunar systems including ISRU for human missions
- Robotics and Vehicles can operate independent pre-established infrastructure
- Restoration from Hibernation requires an Active Main Bus with “*Dawn Mode*”
 - Capable of operating in extreme cold
 - Capable of operating on solar array output alone
- Hibernation improves survival and recovery options in contingency situations
- **Ultimately:** *Hibernation technologies will lead to more robust robotic systems that are actually designed for the Lunar Environment.*

Acknowledgements



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